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ON SIGNAL DECREASE IN HF CIRCUITS DURING PCA EVENTS

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AIR FORCE SYSTEMS COMMAND
United States Air Force

Abstract

The principal morphological features of ionospheric absorption of cosmic radio noise at vertical incidence –due to influx into the polar inosphere of solar protons with particle energy near 10 MeV, and as measured by ground-based riometers operated usually at 30 MHz– are reviewed with figures and brief descriptions. HF signal-intensity observations in two oblique-incidence circuits, Thule to College and Pt. Barrow to Kenai (Alaska), are compared with riometer measurements for several PCA events. In each event the signal in an affected circuit rapidly decreased by the order of 40 dB as soon as the riometer absorption rose by about 1 dB. The signal decrease remained as high as, or even exceeded 40 dB so long as the riometer absorption exceeded a few to several decibels. Even when the riometer absorption has subsided to low values, the signal decrease may remain high because of disturbed ionospheric conditions caused by geomagnetic storms. The observed large signal decrease of ~40 dB is much smaller than the absorption of ~more than 100 dB to be expected (on the assumption that the signal passed completely through the D region) in oblique-incidence circuits during intense PCA periods. It is suggested that a "stand-by" propagation mode, involving a combination of scattering and ducting of HF radio waves near the ionospheric-bottom-boundary, comes into play. It is also suggested that, during disturbed ionospheric conditions, diminutions in ionospheric electron density –in addition to, or in conjunction with, increased ionospheric absorption– is an important contributing cause to HF radio blackouts

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1. INTRODUCTION

It is well known that polar cap absorption (PCA), as determined by increased absorption of high frequency (HF) radio waves at vertical incidence in the polar ionosphere, is caused by an influx, following some solar flares, of greater than 10 protons (with energies near 10 MeV) per cm^2/sec/ster, as measured with orbiting satellites near the earth. The solar-terrestrial relationships, and the atmospheric processes, involved in PCA events have been reviewed a number of times since PCA became identified with regard to cause for the IGY period (Bailey, 1959; Reid, 1961; Weir, 1961; Bailey, 1964; Adams and Masley, 1965; and Hultquist, 1968). Rocket-borne probes have been used in PCA investigations (Ulwick, 1972). Ground-based observations on microwave burst spectra of the sun have been studied as a useful predictor of PCA or solar-proton events (Castelli and Aarons, 1970; Straka and Barron, 1970; and Castelli and Guidice, 1972). Vertical-incidence absorption data from riometer stations (Cormier, 1970) and proton-flux data from satellites (Solar-Geophysical Data, 1968 and later) provide continuing information on PCA events. Smart and Shea (1971) introduced a 3-digit index (relating to solar proton flux at energy levels above 10 MeV, daylight polar riometer absorption at 30 MHz, and sea-level neutron monitor increase) for classifying the magnitude of PCA events.

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The morphological features of the proton flux and vertical-incidence riometer absorption, associated with PCA events, are shown in Section 2 with figures and brief descriptions.

Signal-intensity data from HF oblique-incidence circuits during PCA, published by Egan and Peterson (1960) and by Jelly (1963), and some unpublished data (Davis, 1969) are presented in Section 3. The available data do not provide quantitative estimates on the magnitude of signal decrease in oblique-incidence circuits, because of noise and interference in the circuits, when riometers recorded cosmic noise absorption of more than few decibels.

From the Egan-Peterson report, it can be inferred that the signal decrease in an oblique-incidence circuit may be only of the order of 40 dB when riometers recorded vertical-incidence absorption of 12 dB. Theoretical calculation would estimate the oblique-incidence absorption to be of the order of 500 dB –if the propagated signal actually passed through the D region twice. Instead of this, it is suggested in Section 4 that the propagated signal, after ascending to the bottom of the ionosphere, conceivably follows a chordal trajectory along the ionospheric bottom boundary until it descends to the receiving site.

2. PROTON FLUX AND RIOMETER (VERTICAL-INCIDENCE) ABSORPTION

Figure 1 shows the time history of the proton flux (for particle energy equal to and above 10 MeV) measured in the Explorer 34 satellite (ESSA, 1968), and vertical-incidence absorption measured at 30 MHz by the riometer at Thule, during the PCA event in June, 1968. The square root of the flux is approximately proportional to the absorption, with the constant of proportionality between 1.9 and 2.8 in this event. The good correlation between solar proton flux and riometer absorption has been studied by Kuck (1970).

At the time of a causative proton-event flare on the sun, which precedes the onset riometer absorption usually by one-half to many hours, estimates can be made on the onset time of riometer absorption, on the time and amplitude of maximum proton flux, and on the decay rate of the flux –provided the flare in on the visible side of the solar disk. These estimates are based on solar radio emissions at several frequencies over a wide band, on the heliocentric angular separation between the flare position and the magnetic field line starting from the sun and intercepting the earth, and on solar-wind velocity (Castelli and Aarons, 1970; Straka and Barron, 1970; and Smart and Shea, 1969).

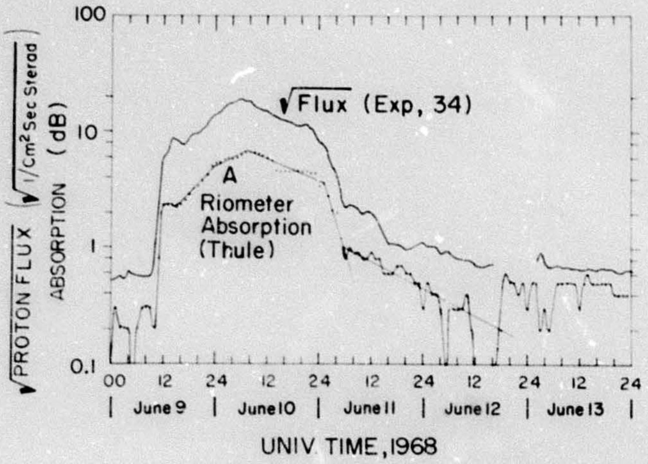

Figure 1. Riometer Absorption at 30 MHz in Thule, and Proton Flux for Particle Energy ≥ 10 MeV in Orbiting Satellite During PCA Event in June 1968

Owren (1969) has shown that by grouping data in hourly intervals (with four or more data points per hour), curves of maximum, average, and minimum riometer absorption or proton flux can be forecast which best fit a few hours of real-time data. Figure 1 shows that piecewise-linear extrapolations of the logarithmic values of riometer absorption or proton flux give acceptable forecasts of the observed values –with four hours of lead time during some linear segments, and up to 24-h during one segment.

The fractional reduced-absorption ratio, R, during night hours –measured from the linear-decrease reference line in Figure 2– is shown in Figure 3 as a function of the solar zenith angle in Thule, where the corrected magnetic latitude is 86.0 deg (Hakura, 1965). The corresponding curve (Reid, 1969) for Great Whale River, at magnetic latitude = 68.2 deg, during the same event is also shown. Thus, the dependence of R on the solar zenith angle varies for stations at different magnitude latitudes.

Aside from the night-time reduction in vertical-incidence, riometer absorption, there is also an occasional mid-day reduction in riometer absorption –which occurs for 20 percent of PCA events, and sometimes in only some riometer stations (Leinbach, 1967).

Except for the night-time reduction, and the occasional mid-day reduction, the riometer-measured absorption is relatively uniform within the whole polar region, bounded by a locus of constant corrected magnetic latitude at any instant of time during a PCA event. This uniformity is subject to fluctuations of a few decibels, due to aurora-induced absorption (Weir, 1961; Leinbach, 1962; and Hakura, 1969).

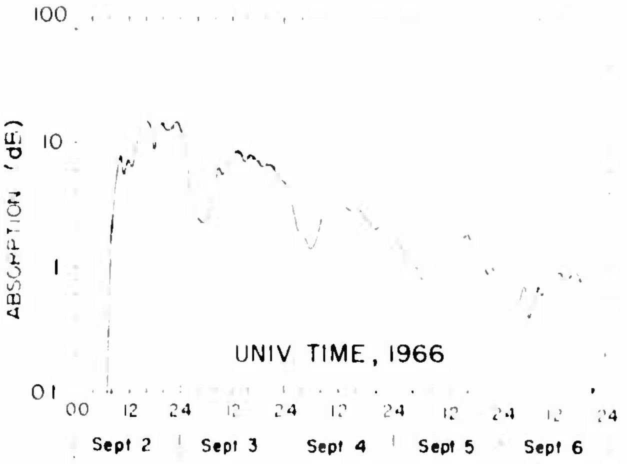

Figure 2. Riometer Absorption at 30 MHz in Thule During PCA Event in September 1966

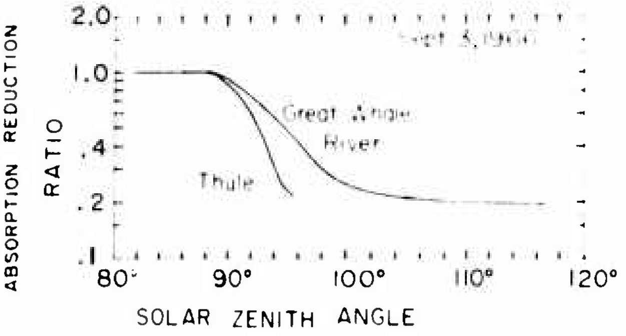

Figure 3. Night-Time Absorption Reduction Ratio as Function of Solar Zenith Angle for Thule (86.0° N) and Great Whale River (68.2° N) During PCA Event in September 1966

The onset and terminating times of riometer-measured absorption for ten PCA events are shown as function of corrected magnetic latitude in Figure 4. The upper part of the figure pertains to eight events of the IGY period, and was scaled from large original graphs plotted by Leinbach (1962) from riometer records. The lower part of Figure 4 pertains to two events in May, 1967 (Ecklund, 1969). The dates and onset times of riometer absorption for the events represented by the curves, labeled 1 through 10 in Figure 4, are listed in Table 1.

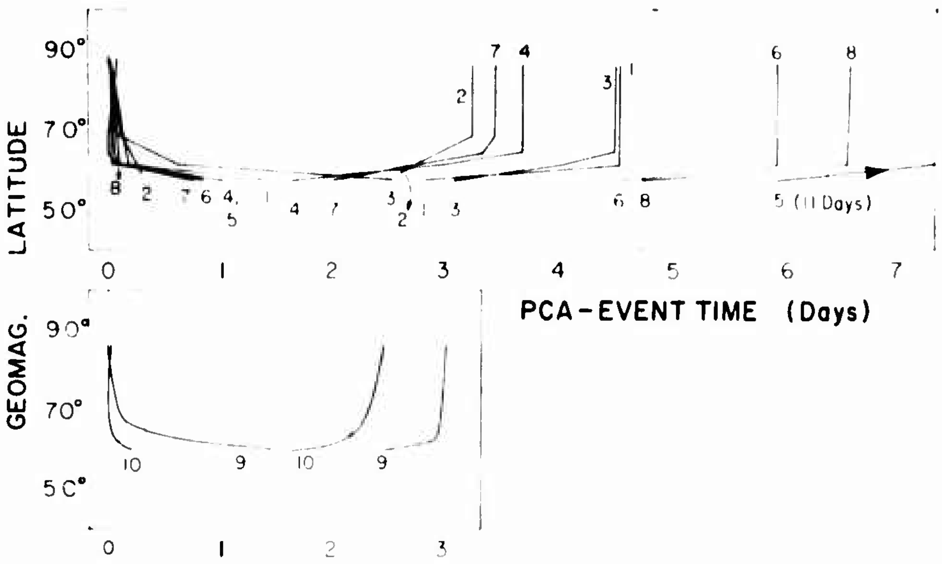

Figure 4. Relative Onset and Terminating Times as Functions of Geomagnetic Latitudes for PCA Events Listed in Table 1

Table 1. Dates and Onset Times of Riometer Absorption for the PCA Events in Figure 4

Curve No.	Date and Onset Time
1	June 7, 1958, 00 UT
2	August 16, 1958, 00 UT
3	August 21, 1958, 13 UT
4	August 21, 1958, 00 UT
5	May 11, 1959, 00 UT
6	June 10, 1959, 04 UT
7	June 14, 1959, 06 UT
8	June 16, 1959, 22 UT
9	May 24, 1967, 00 UT
10	May 28, 1967, 06 UT

The longest-lived event (curve No. 5) in Figure 4 lasted 11 days. The onset-time diagrams do not, while the terminating-time diagrams do, show large variations for the different events. The curves 6, 7, and 8 represent sequentially overlapping events; the right-hand portions of diagrams 6 and 7 represent, respectively the terminating time for event 6 had event 7 not intervened, and for event 7 had event 8 not intervened.

The vertical distributions of ionospheric D-region electron density are available, from rocket-borne or multi-frequency ground-based riometer measurements, for some PCA events (Musser, 1969; Ulwick, 1972). Typical electron-density profiles, and nominal collision-frequency profiles calculated from standard atmospheric-density distributions, are shown in Figure 5. These profiles provide data for attempted evaluation of signal-intensity levels, depending on modes of propagation, in oblique-incidence circuits during PCA events.

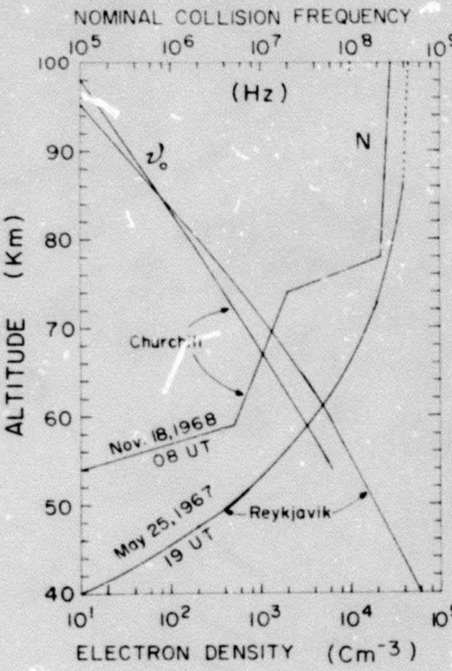

Figure 5. Height Profiles of Electron Density and Nominal Collision Frequency During PCA Events in May 1967 at Reykjavik, Iceland and in November 1968 at Fort Churchill, Canada

3. SIGNAL DECREASE AND LUF INCREASE IN OBLIQUE-INCIDENCE CIRCUITS

In constrast with the solar proton flux and the vertical-incidence riometer absorption, the signal-intensity decrease in oblique-incidence circuits during periods of intense riometer absorption (of much more than few dB) is not too well delineated.

During PCA events, the lowest observed (or "useable") frequency in oblique-incidence ionograms increases, as expected. The observed increase, Δ(LUF), is shown in Figure 6 for four circuits –Resolute Bay - Churchill, Resolute Bay - Ottawa, Churchill - Ottawa, and Ottawa - Hague (Holland)– during the PCA event beginning in 28 Sept, 1961 (Jelly, 1963). The 30 MHz riometer absorption in Churchill increased to 8 dB at maximum in 30 Sept, then decreased to residual level in 1 October. Substantial reduction in riometer absorption occurred during the intervening nights. Radio "blackout" (during which no frequency in the HF band is

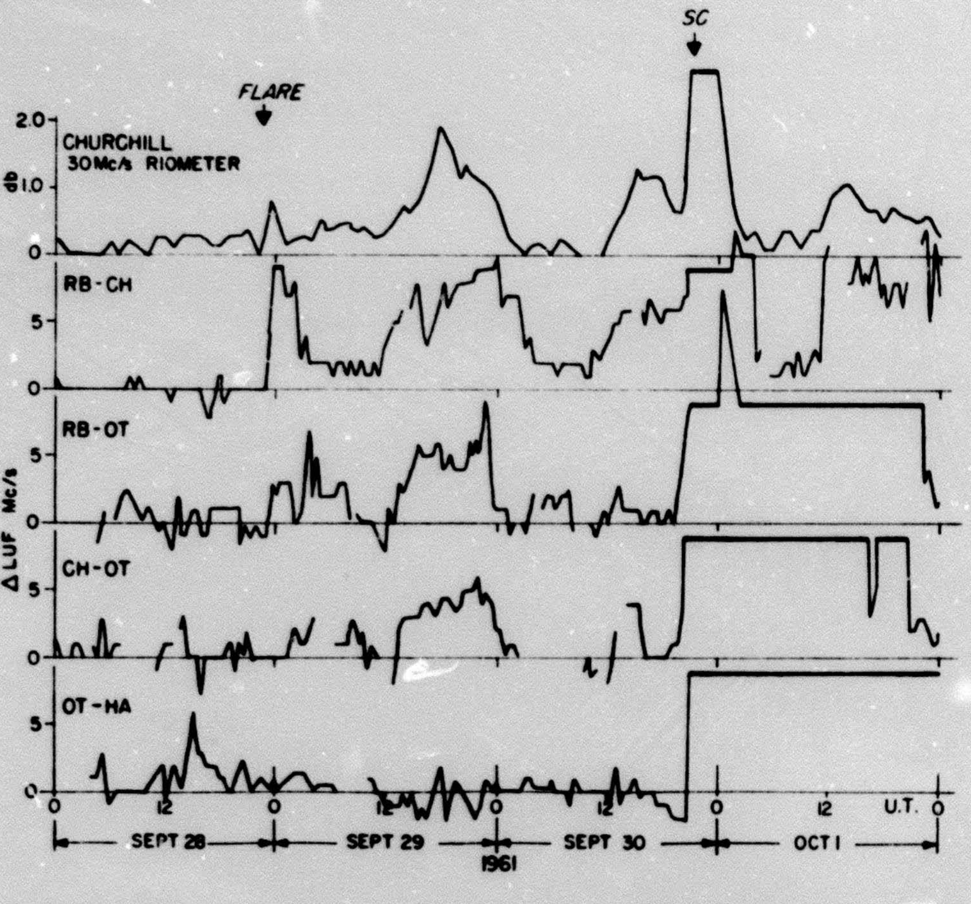

Figure 6. Polar-Cap Absorption Event Beginning 28 Sept, 1961, on (a) 30 MHz Riometer at Churchill, (b) Lowest Useable Frequency on the Resolute Bay - Churchill Path, (c) the Resolute Bay - Ottawa Path, (d) Churchill - Ottawa Path, and (e) Ottawa - Hague Path (Jelly, 1963)

received, and which is indicated by heavy horizontal bars in Figure 6) occurred in all four circuits during the maximum riometer-absorption phase, and with the exception of the RB - CH circuit during nearly the entire duration of the decaying phase of riometer absorption. The blackout was associated (Jelly, 1963) with the main phase of the magnetic storm which followed its sudden commencement (SC), in Figure 6 (sometimes a SC does not accompany a main-phase magnetic storm).

During a main-phase storm, aurora-induced absorption arises, and substantial diminutions occur in the F-region critical frequency over large areas. Radio blackouts, and related effects, are usually interpreted as being caused mainly by increased absorption of radio waves -to the neglect of another cause. As blackout did not occur during the increasing riometer-absorption phase of the event in Figure 6 -when the riometer absorption was considerably higher than during the decaying phase- it is clearly necessary to invoke another cause, namely the diminution in foF2 and concomitant ray-pattern effects, as an important contributing factor in blackouts.

Figure 7 (Jelly, 1963) shows the observed dependence on frequency of the increase in oblique-incidence absorption in the Resolute Bay - Ottawa circuit; the observed curve was measured during a 3-min interval in 29 Sept when the vertical-incidence riometer absorption in Churchill was near 1 dB (see Figure 6). For comparison a calculated curve, extrapolated (with respect to the secant law for path obliquity and inverse frequency-squared law for frequency dependence) from the 30 MHz riometer data in Churchill is also shown in Figure 7. The agreement between the observed and calculated curves is satisfactory -in this case of weak riometer absorption.

Figures 8 and 9 include signal-intensity data in oblique-incidence circuits during periods of intense vertical-incidence riometer absorption.

Figure 8 (Egan and Peterson, 1960) compares riometer absorption at 27.6 MHz at Thule and College, Alaska, with signal intensity at 12 MHz in the Thule-College circuit during a sequence of four large PCA events occurring between 26 April and 15 May, 1960. (In 4 May an additional sharp peak occurred in the riometer absorption in Thule but not in College; this presumably constituted a short-lived event localized in a small region near the magnetic pole.) In each of the four large events, the signal intensity rapidly decreased by approximately 40 dB (or more?), while the riometer absorption increased by only about 1 dB; then the signal persisted near the minimum level for nearly the entire duration of the event, while the riometer absorption rose to as high as 14 dB, and then decayed to the 1 dB level.

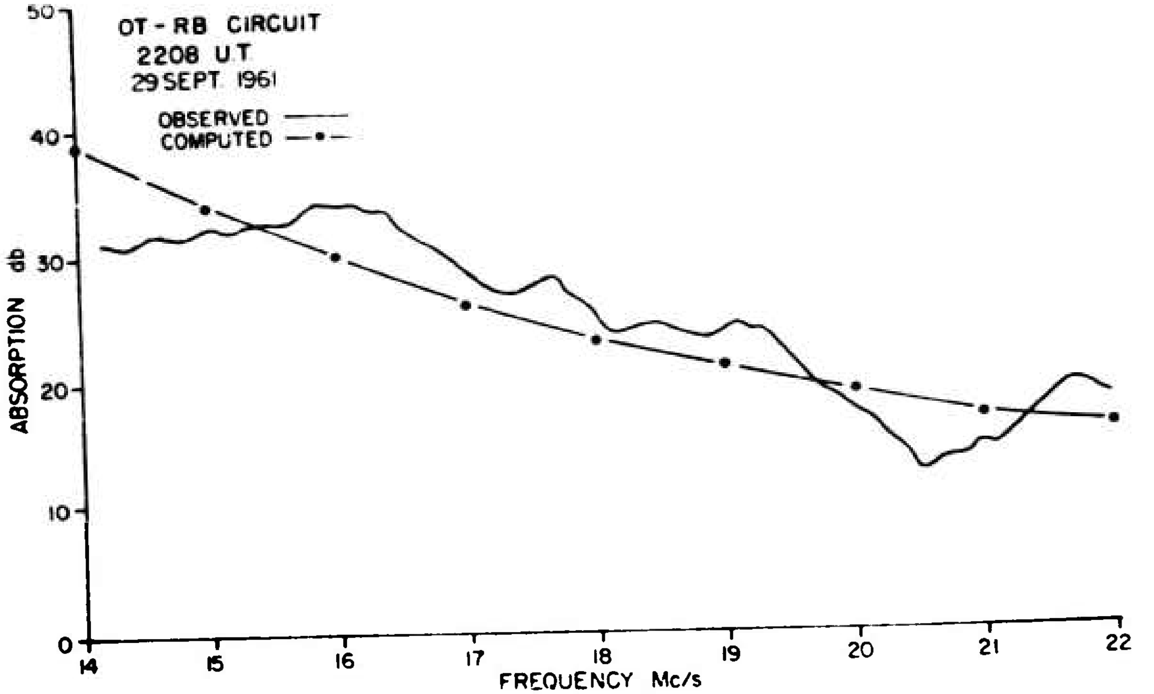

Figure 7. Absorption Measured on 29 Sept on the Resolute Bay - Ottawa Path Compared With Oblique-Incidence Absorption Extrapolated from 30 MHz Vertical-Incidence Riometer at Churchill (Jelly, 1963)

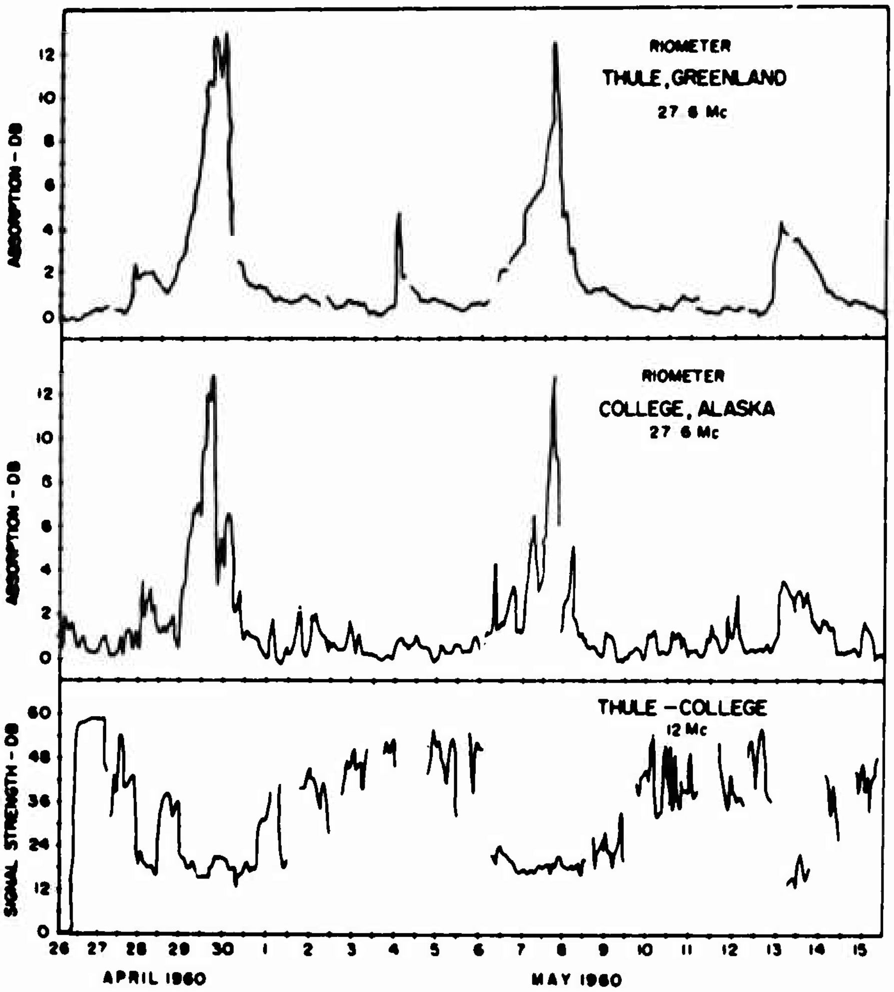

Figure 8. Signal Strength Observations on the Thule-to-College Circuit and Riometer Measurement at Thule and College During the Period 26 April to 15 May 1960 (Courtesy Egan & Peterson, 1961)

For the same 26 April to 15 May, 1960 period as in Figure 8, the signal intensity observed at 5.13, 9.95, 14.7 and 19.2 MHz in a 1200 km path, namely a geographically north-south path from Pt. Barrow to Kenai, Alaska, is shown in Figures 9(a), 9(b) and 9(c). The data-point dots shown were plotted from unpublished numerical tabulations of hourly averaged values processed from signal-intensity recordings measured under the direction of R. Silberstein of the Institute of Telecommunication Sciences, Boulder, Colorado (Davis, 1969).

In Figure 9 the receiver noise levels were as follows:

Frequency (MHz)	Minimum Receiver Noise Level (dB)
5.13	−170
9.95	−180
14.7	−160
19.2	−160 to −170

The vertical bars indicate that the received signal intensity was below the upper end of each bar, and was uncertain due to the presence of competing noise and interference. The magnitude of the signal sometimes became uncertain at a level as much as 40 dB above the minimum receiver noise. A horizontal bar underlying a data-point dot indicates that the recorded signal includes an extraneous contribution (such as noise or from an interfering station) in addition to the carrier signal from the Pt. Barrow transmitter.

The solid-line curve shows the vertical-incidence absorption of cosmic noise measured with a riometer at 27.6 MHz in Thule (Leinbach, 1962).

In Figure 9 there are time intervals, different for different frequencies, during which the signal level was very low when the riometer absorption was low. These intervals of low signal are clearly due to non-absorption causes −the receiver site's being within the skip zones of ionospherically transmitted rays, low ionization in the F2 layer, and effects of horizontal ionization gradients in the polar ionosphere.

In the opposite sense, there are time intervals in Figure 9 during which the signal decrease, which follows in step with riometer-absorption increase, is much smaller than expected on conventional reasoning. If it is assumed that the received signal passed completely through the ionospheric D region (twice, upward and downward), and that absorption in decibels follows the inverse frequency-squared dependence, then an increase of one dB in absorption as measured by riometer at vertical incidence and 27.6 MHz would cause a signal decrease of 19 dB in the oblique-incidence path from Pt. Barrow to Kenai for the transmission frequency of 9.95 MHz. This theoretical estimate gives absorption values for the Pt. Barrow-to-Kenai path which are too high by tens of dB to more than 100 dB, when the riometer registered an absorption increase larger than 2 dB.

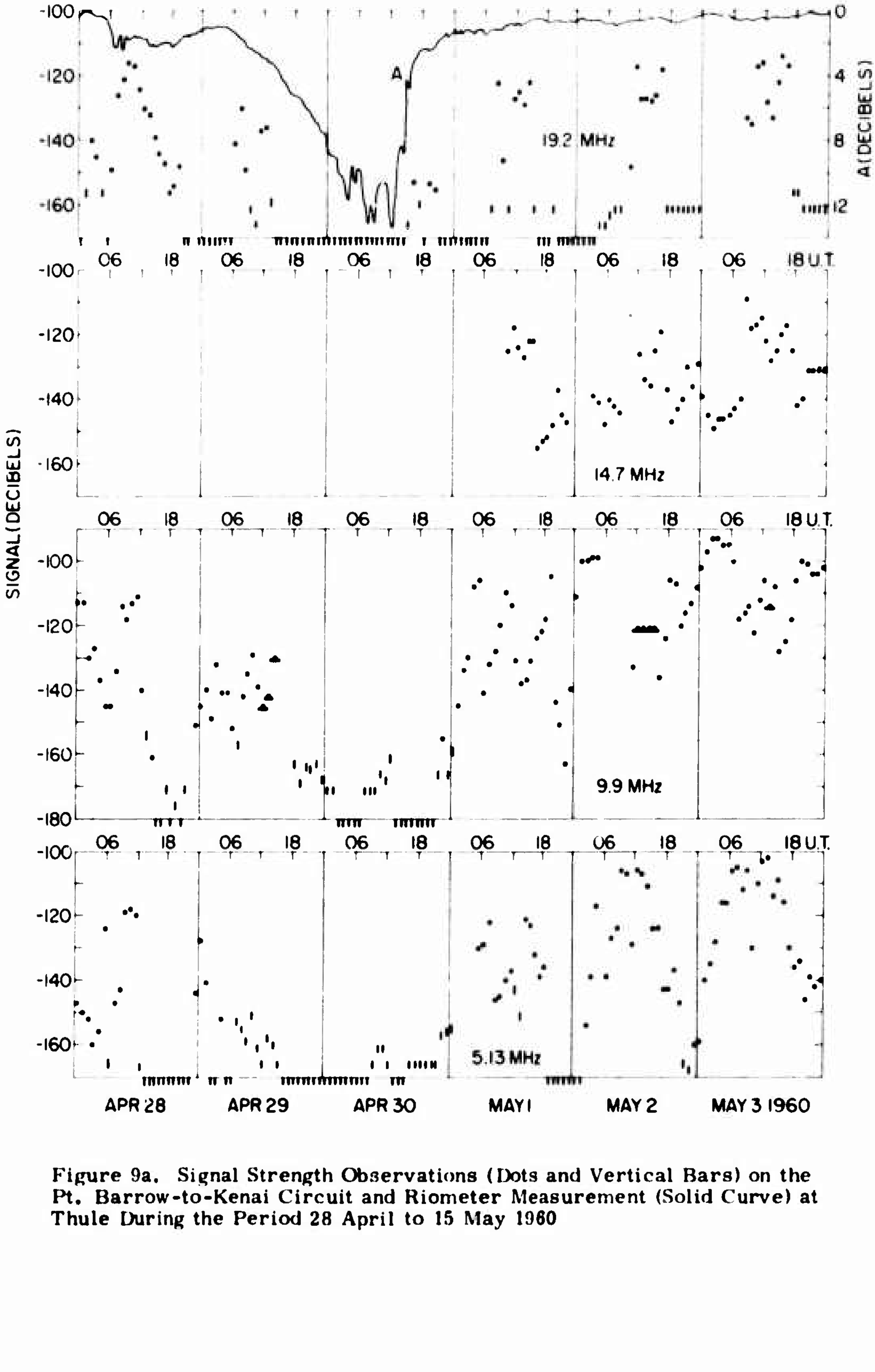

Figure 9a. Signal Strength Observations (Dots and Vertical Bars) on the Pt. Barrow-to-Kenai Circuit and Riometer Measurement (Solid Curve) at Thule During the Period 28 April to 15 May 1960

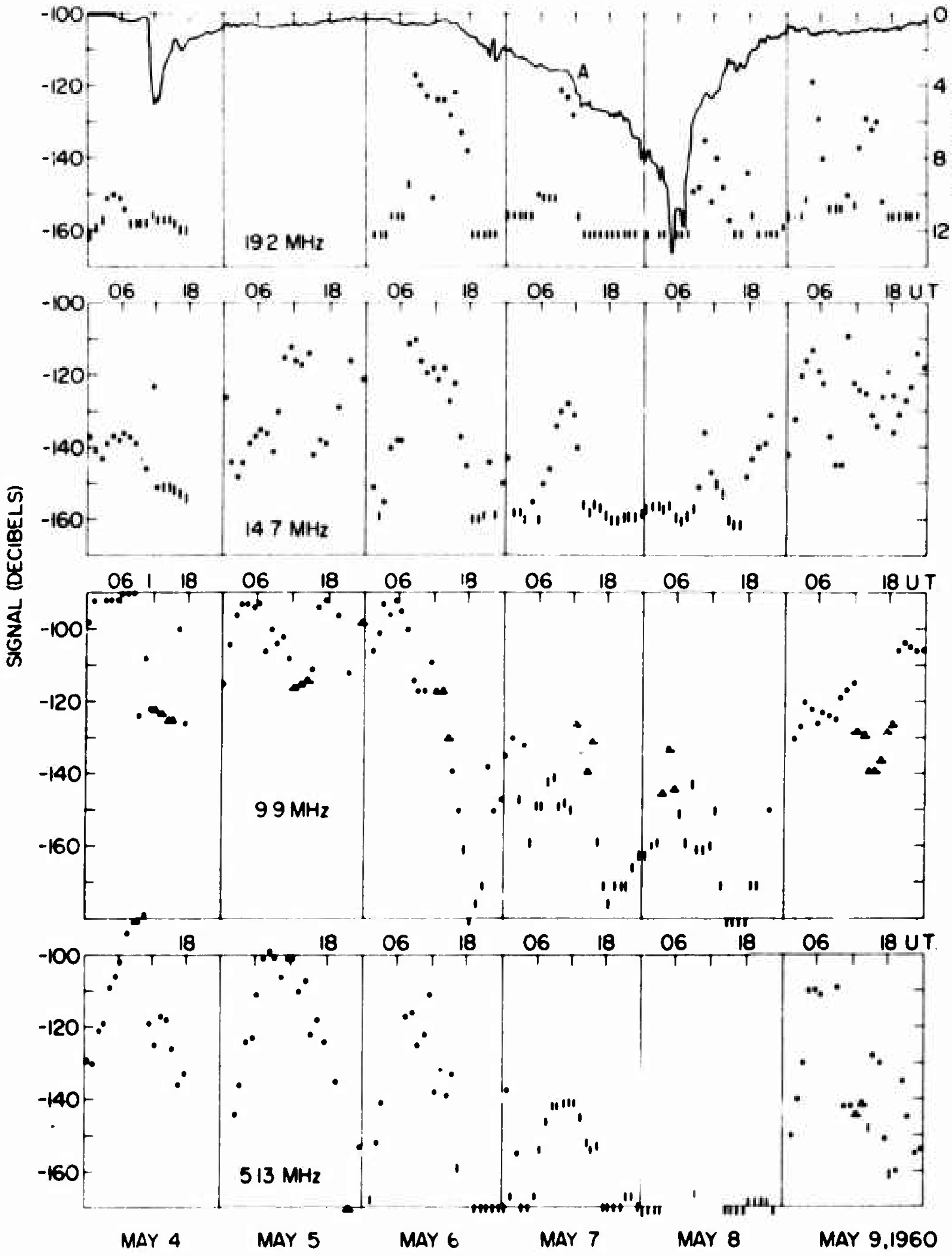

Figure 9b. Signal Strength Observations (Dots and Vertical Bars) on the Pt. Barrow-to-Kenai Circuit and Riometer Measurement (Solid Curve) at Thule During the Period 28 April to 15 May 1960

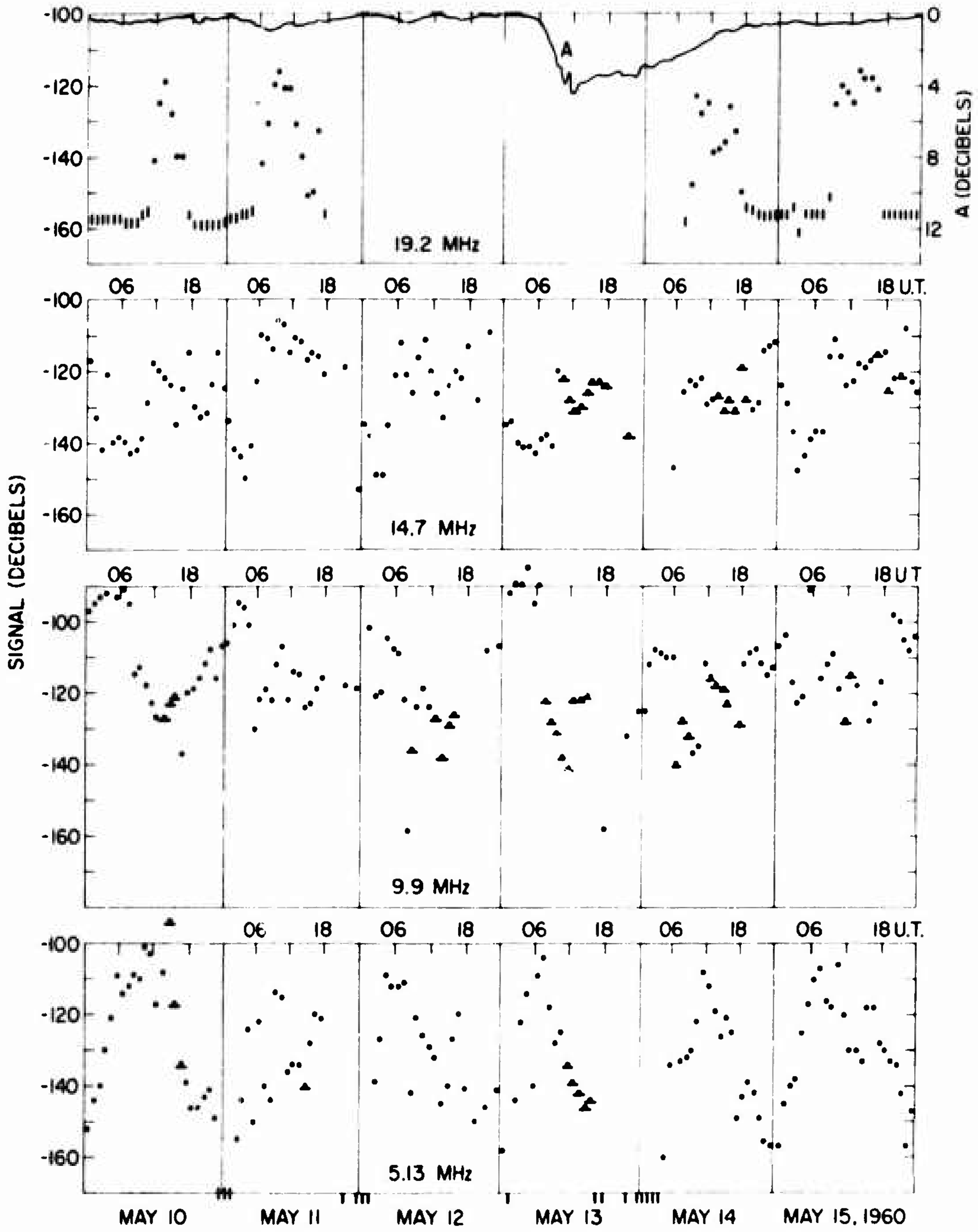

Figure 9c. Signal Strength Observations (Dots and Vertical Bars) on the Pt. Barrow-to-Kenai Circuit and Riometer Measurement (Solid Curve) at Thule During the Period 28 April to 15 May 1960

The high values of calculated signal decrease cannot be reduced materially as long as one adheres to the point of view that the propagated signal passes completely through the D region (twice) before reaching the receiving site. This is so in spite of the fact, frequently but irrelevantly cited, that the absorption coefficient (in dB per unit height interval in the ionosphere) varies as f^n, as some power of the frequency with n taking on values distributed between 0 and -2 (depending on the relative values of the frequency f and the electron-neutral collision frequency, which varies logarithmically with altitude in the ionosphere). It turns out that for rather widely different samples of electron-density and collision-frequency profiles, as shown in Figure 5, the absorption coefficient attains maximum values at a range of altitudes such that the relevant total absorption (obtained by integrating the absorption coefficient, in dB/km, over the altitude intervals of the D and E regions) would deviate only slightly from the inverse frequency-squared law, for frequencies down to 10 MHz.

Some data on this issue are available from rocket borne measurements conducted during a polar-cap-absorption event (Chidsey, 1972). These measurements show that the integrated absorption through the D region plus part of E region varies in accordance with the reciprocal frequency, 1/f, raised to an exponential power between 1.4 and 2.0; this law was observed for frequencies down to 9 MHz, the lowest frequency of the measurements reported by Chidsey.

4. CONCLUSIONS, AND SUGGESTION OF HF DUCTING AND SCATTERING NEAR THE IONOSPHERIC BOTTOM BOUNDARY DURING PCA

The principal morphological features of ionospheric absorption of cosmic radio noise, as measured at vertical incidence by riometers operated frequently at 30 MHz, during solar-proton events are satisfactorily understood and well delineated –such that ground-based measurements of riometer absorption, and equivalently satellite-borne measurements of solar-proton flux near the earth, can be extrapolated in real time, with lead times of a few or more hours.

The onset of riometer absorption in the polar ionosphere can often be forecast by observations on the solar microwave burst spectra over a wide frequency band, when solar flares occur.

The correlation during solar-proton events between (a) vertical-incidence riometer absorption and (b) signal-intensity decrease in HF oblique-incidence circuits is poor. Nonetheless, when the onset of increased riometer absorption occurs in a solar-proton event, the signal intensity in an affected oblique-incidence circuit rapidly decreases by the order of 40 dB –as soon as the riometer absorption rises by about 1 dB. Thereafter, the signal decrease remains as high as, or perhaps considerably exceeds, 40 dB so long as the riometer absorption exceeds a few to several dB. Even for periods when the riometer absorption subsides to low values, the signal decrease in oblique-incidence circuits may still be high because of disturbed ionospheric conditions prevailing during geomagnetic storms which often follow a storm's sudden commencement occurring near the time of maximum riometer absorption in a PCA event.

Observational evidence during PCA events provide signal-decrease values that are extremely remote from the more than 100 dB expected on the assumption that the propagated signal passes completely through the ionospheric D region.

In view of the fact that the signal decrease in oblique-incidence circuits has actually been observed, on occasions, to be of the order of only 40 dB, when the vertical-incidence riometer absorption exceeded 5 dB, it is suggested that a "stand-by" propagation mode comes into play during PCA events -when ionospheric absorption exacts a toll of 40 dB or more from the signal intensity in oblique-incidence circuits. This stand-by mode is conceived to be a combination of ducting and scattering of HF radio waves near the bottom boundary of the ionospheric D region, and requires further investigations. The "stand-by" mode presupposes the presence, at the ionospheric bottom boundary, of sufficient irregularities in the spatial distribution of electron density during the influx of solar protons into the polar ionosphere. Relatively slight deviations from a smooth particle-flux vs energy spectrum, near 10 MeV, may conceivably suffice to produce the required irregularities.

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